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CHROMOSPHERICALLY ACTIVE STARS. I. HD 136905

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ABSTRACT

The variable star HD 136905, recently designated GX Librae, is a chromospherically active K1 III single-lined spectroscopic binary with a period of 11.1345 days. It has moderate strength Ca II H and K and ultraviolet emission features, while Hα is strongly in absorption. The inclination of the system is $58° \pm 17°$ and the unseen secondary is most likely a G or K dwarf. The v sin$i$ of the primary, 32 ± 2 km s^{-1}, results in a minimum radius of 7.0 ± 0.4 $R_{\odot}$. Since the star fills a substantial fraction of its Roche lobe, the double-peaked light curve seen by photometric observers is predominantly ellipsoidal in nature. Both the photometry and the spectroscopy yield values for the period and the time of conjunction that are identical within their uncertainties.

I. INTRODUCTION

Bidelman and MacConnell (1973) detected Ca II H and K emission in HD 136905 ($\alpha = 15^h 18^m\!.1$, $\delta = -06°15'$, 1900) and classified it K1 III + F. As a variable star it recently has been designated GX Librae. From eight radial velocities, Burke *et al.* (1982) found two possible orbital periods, a more likely one at 11.12 days and a second at half that value. With the 11.12-day period their photometric observations of 1980 showed a double sine curve with two similar maxima per cycle and an amplitude of 0.07 mag. The photometry of Bopp *et al.* (1983), obtained during the same time interval, confirmed the amplitude of the variability and showed the same factor 2 ambiguity in the period. In this paper we present observations which show that the longer orbital period is the correct one and discuss other properties of this RS CVn-type binary.

II. OBSERVATIONS AND REDUCTIONS

The high-dispersion ground-based spectroscopic observations were obtained at McDonald and Kitt Peak Observatories with a variety of solid-state detectors (Table I). All observations were made in the red region of the spectrum and have signal-to-noise ratios ranging from 30 to 150. Most of the observations were centered at 6420 Å (Fig. 1) but several were centered at Hα (Fig. 2). The radial velocities (Table II) were determined relative to α Boo or μ Her, which have radial velocities of -5.3 km s^{-1} (Pearce 1955) and -15.6 km s^{-1} (Wilson 1953), respectively. Details of the cross-correlation reduction procedure have been given by Fekel, Bopp, and Lacy (1978).

One ultraviolet spectroscopic observation was obtained with the short-wavelength primary (SWP) camera of the *International Ultraviolet Explorer* (*IUE*) satellite. This 150 min exposure, SWP 22253, obtained through the large ($10'' \times 20''$) aperture, has a resolution of about 6 Å and covers a wavelength region from 1100 to 2000 Å. The observation was absolutely calibrated with the standard computer software routines at the Regional Data Analysis Facility of the Goddard Space Flight Center.

With the 16 in. Cassegrain at Braeside Observatory (Fried 1983, 1984) on 19 nights in 1983, Fried observed HD 136905 differentially with respect to the comparison star HD 136480 = BD$-6°$4181, the same one used by Burke *et al.* (1982) and Bopp *et al.* (1983). He made generally three comparisons on each night and the resulting nightly means, corrected for atmospheric extinction and transformed to V of the *UBV* system, are listed in Table III, where Δ is in the sense variable minus comparison. Except for the two nights marked with a colon, the internal mean error was less than $\pm 0^m\!.01$.

III. ORBIT

Twenty-nine high-dispersion spectroscopic observations obtained between 1980 and 1984 (Table II) were used to determine the orbital elements. None of these observations show any indication of a secondary component. The period-finding program of Deeming (Bopp *et al.* 1970) was used to determine a preliminary period. Then, preliminary orbital elements were determined with a slightly modified version of the computer program of Wolfe, Horak, and Storer (1967), which uses the Wilsing-Russell method. Final orbital elements (Table IV) were computed with the differential corrections program described by Barker, Evans, and Laing (1967). The formal solution gave a value for the eccentricity of 0.017 ± 0.010 so, in accordance with the precepts of Lucy and Sweeney (1971), an $e = 0$ solution has been adopted. The observed radial velocities and the computed radial velocity curve are plotted in Fig. 3.

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TABLE I. Telescope-detector combinations.

Telescope	Detector	Dispersion (Å mm^{-1})	Resolution (Å)	Wavelength range(Å)	Source code
McDonald 2.7 m	Reticon	4.4	0.36	110	MR
Kitt Peak coudé feed	Fairchild CCD	14.8	0.45	165	KF
	RCA CCD	4.2	0.3	65	KR
	TI CCD	4.2	0.21	50	KT1
	TI CCD	7.6	0.23	90	KT2

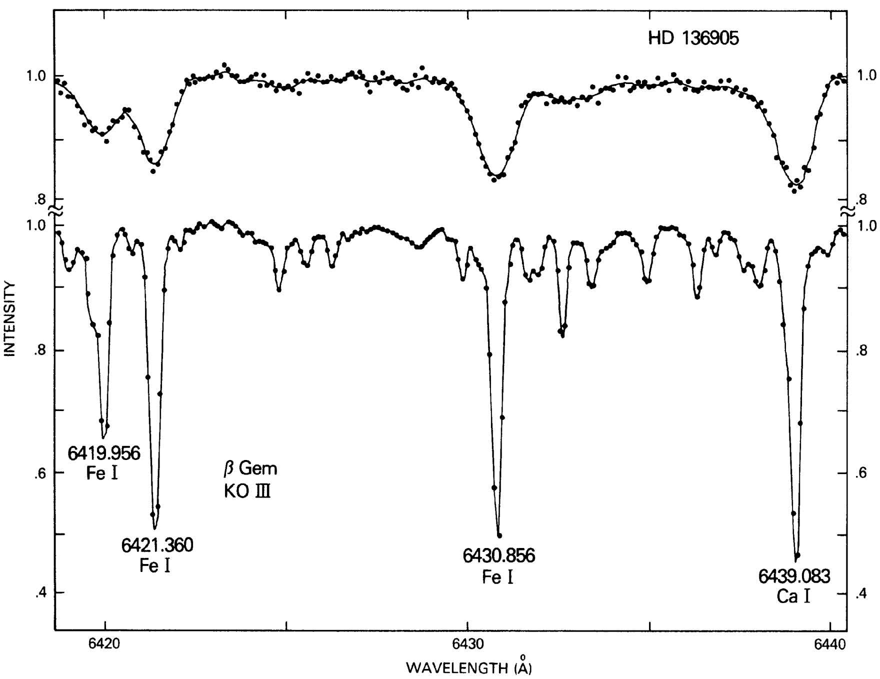

FIG. 1. Portion of a Reticon observation of HD 136905 centered at 6420 Å compared with that of β Gem. The line broadening of HD 136905 is quite obvious.

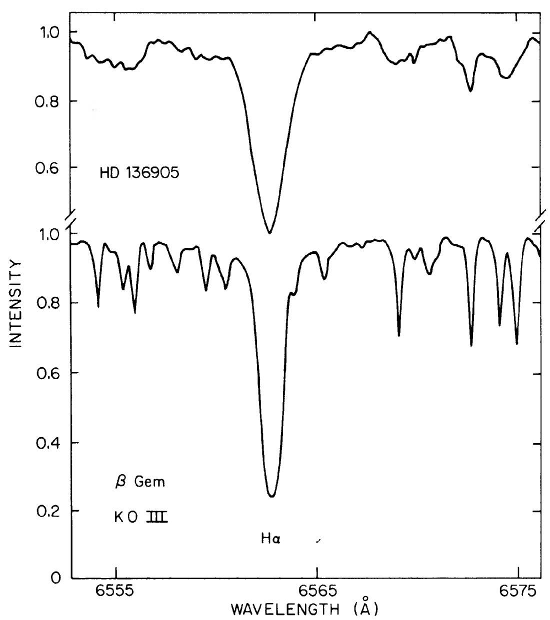

FIG. 2. Portions of two Reticon observations comparing the Hα line of HD 136905 with β Gem, an inactive K0 III.

TABLE II. Radial velocities of HD 136905.

HJD 2440000 +	Phase	V (km s^{-1})	O − C (km s^{-1})	Source
4355.901	0.847	80.7	3.2	MR
4357.894	0.026	99.9	0.0	MR
4627.037	0.198	76.6	2.3	MR
4628.057	0.289	49.7	− 2.7	MR
4736.800	0.056	97.7	− 0.4	MR
4737.687	0.135	88.3	1.0	MR
4738.704	0.227	66.0	− 1.5	MR
4739.776	0.323	44.5	− 0.3	MR
5075.858	0.507	23.1	− 0.2	KF
5076.869	0.597	33.0	2.7	KF
5077.859	0.686	46.2	− 0.6	KF
5078.834	0.774	68.4	0.8	KF
5079.866	0.867	86.8	− 0.8	KF
5357.041	0.760	63.0	− 1.2	KR
5358.055	0.851	86.4	1.7	KR
5359.022	0.938	97.8	0.3	KR
5361.025	0.118	90.8	0.5	KR
5361.986	0.204	72.0	− 0.8	KR
5447.890	0.919	96.3	0.8	KR
5449.914	0.101	93.2	0.3	KR
5450.880	0.188	78.7	2.1	KR
5525.772	0.914	93.6	− 1.3	KT1
5596.602	0.275	54.8	− 0.9	KT2
5598.599	0.454	24.1	− 0.7	KT2
5720.022	0.360	37.3	− 0.0	KT2
5721.022	0.449	25.1	− 0.1	KT2
5811.869	0.608	31.4	− 0.4	KT2
5853.749	0.369	36.3	0.7	KT2
5854.778	0.462	24.4	0.0	KT2

TABLE III. 1984 Photometry of HD 136905.

JD (hel.)	ΔV
2445447.8413	$-0^{m}0507$
2445457.8667	−0.0047
2445458.7979	−0.0430
2445461.9331	+0.0480:
2445464.8042	−0.0343
2445469.8223	−0.0377
2445470.7969	−0.0640
2445471.8003	−0.0480
2445472.8901	+0.0010
2445477.7993	−0.0253
2445485.7578	+0.0247
2445487.7827	−0.0543
2445492.7554	−0.0710:
2445493.7934	−0.0710
2445497.7780	−0.0070
2445498.7695	−0.0497
2445499.8120	−0.0417
2445500.7559	−0.0257
2445501.7573	+0.0040

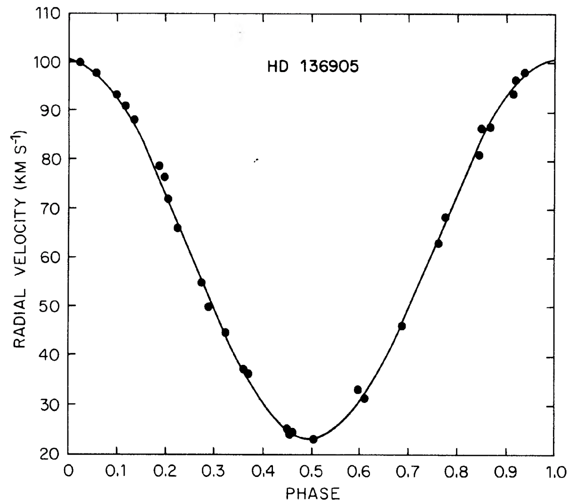

FIG. 3. Observations and computed radial-velocity curve of HD 136905. Phase is computed from T_0, the time of maximum positive velocity.

IV. ACTIVE-CHROMOSPHERE CHARACTERISTICS

The Ca II H and K emission in this late-type star was first detected, though noted as uncertain, by Bidelman and MacConnell (1973). Fekel, Moffett, and Henry (1986) confirmed its presence and found it to be moderate in strength, class C on Hearnshaw's (1979) qualitative emission scale.

In most RS CVn binaries Hα is an absorption feature although it is typically weaker, that is, has a smaller equivalent width, than in similar stars that are not chromospherically active (Smith and Bopp 1982). Our Hα observations of HD 136905, such as the one seen in Fig. 2, show a strong absorption feature with an equivalent width of 1.35 Å. For comparison, the Hα line of β Gem seen in Fig. 2 has an equivalent width of 1.29 Å. Thus it appears that the Hα line of HD 136905 is at most weakly active.

The spectrum obtained with the SWP camera (Fig. 4) shows ultraviolet emission features typical of chromospherically active stars. Table V gives the emission feature identifications and the measured observed fluxes. These fluxes were converted into surface fluxes following the procedure of Linsky *et al.* (1979). Since the $V-R$ color of active stars appears to have a color excess relative to inactive ones (Fekel, Moffett, and Henry 1986), a value of $V-R=0.75$ consistent with the observed $B-V$ color was taken from Johnson (1966) for use in determining the surface fluxes.

Compared with the results of Stickland and Williams (1983) for other chromospherically active giants, the surface fluxes of HD 136905 are greater than those of λ And but less than those of σ Gem. Also computed are the relative fluxes, which are distance independent, thus giving the fraction of total stellar luminosity in each line.

TABLE IV. Orbital elements.

$P=11.1345\pm0.0005$ (m.e.) days
$T_0=2445070.222\pm0.017$ (m.e.) HJD
$\gamma=61.8\pm0.3$ km s^{-1}
$K_1=38.6\pm0.4$ km s^{-1}
$e=0.0$ (assumed)
$a_1 \sin i=5.91\pm0.06\times10^6$ km
$f(m)=0.066\pm0.002\ M_\odot$
Standard error of an observation of unit weight $=1.3$ km s^{-1}.

In addition to searching for evidence of chromospheric activity at ultraviolet wavelengths, the spectrum of HD 136905 was obtained to search for the F-type companion suggested by the K1 III + F classification of an objective-prism observation (Bidelman and MacConnell 1973). As can be seen in Fig. 4, there is no evidence of the suspected F-type component (Bidelman and MacConnell 1973) or an earlier-type main-sequence component as was found in HD 158393 (Lloyd-Evans *et al.* 1985), nor a hot degenerate component such as the ones found in 39 Cet (Simon, Fekel, and Gibson 1985) and HD 160538 and HD 185510 (Fekel and Simon 1985).

V. DISCUSSION

As noted previously, Bidelman and MacConnell (1973) classified the system as K1 III + F. Fekel, Moffett, and Henry (1986) obtained average V magnitudes and colors of $V=7.31$, $B-V=1.02$, $V-R=0.84$, and $R-I=0.55$ from three observations. This $B-V$, if assumed unreddened, corresponds to a spectral type of K0 III according to

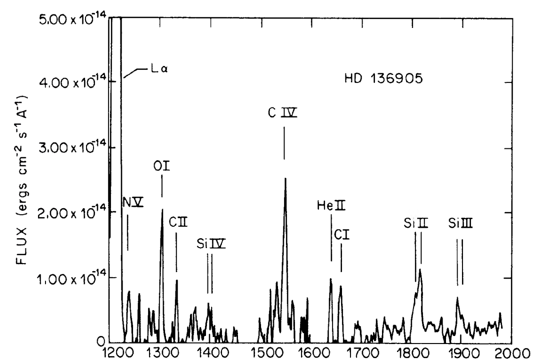

FIG. 4. *IUE* low-resolution short-wavelength observation of HD 136905.

TABLE V. Ultraviolet emission line fluxes (erg cm^{-2} s^{-1}).

Ion	λ (Å)	Observed flux $\times 10^{-14}$	Surface flux $\times 10^{4}$	f_{line}/l_{bol} $\times 10^{-7}$
N V	1240	5.2	2.9	12
O I	1305	13.1	7.2	31
C II	1335	4.2	2.3	10
Si IV	1400	5.3	2.9	13
C IV	1550	16.9	9.3	40
He II	1640	5.7	3.1	14
C I	1657	6.6	3.6	16
Si II	1808, 1817	13.6	7.5	32
Si III	1892	4.0	2.2	10

the color–spectral type relation of Johnson (1966). The $V-R$ and $R-I$ colors show excesses typical of chromospherically active stars (Fekel, Moffett, and Henry 1986).

Since the system is not double lined, it is more difficult to determine properties of the system such as the inclination and the nature of the secondary. Yet some restrictions can be determined. Most of the masses of the active star in RS CVn binaries range from 1.2 to 1.8 $M_\odot$ (Popper 1980). Combining the value of the mass function (Table IV) with each assumed primary mass, we determine the corresponding minimum value of the secondary mass which occurs when $i = 90°$. The upper limit for the mass of the secondary is about 1.1–1.2 $M_\odot$. Such a mass corresponds to a late F-type star, which could be detected at ultraviolet wavelengths in such a system. This upper limit for the secondary mass results in a lower limit for the inclination. Table V gives the results of such calculations. Column 1 is the assumed primary mass. Column 2 is the secondary mass which results in $i = 90°$. Column 3 is the mass ratio. Column 4 is the upper limit to the mass of the secondary, while Column 5 is the inclination resulting from that assumed upper limit. Thus, the lower limit for the inclination of the system is $42° \pm 2°$ and the minimum mass is $0.67 \pm 0.07\ M_\odot$.

Fekel, Moffett, and Henry (1986) determined $v \sin i = 32 \pm 2$ km s^{-1}. This value, combined with a rotational period of 11.1345 days (assuming synchronous rotation), gives a minimum radius $R_1 \sin i$ of $7.0 \pm 0.4\ R_\odot$. From Table IV we see $a_1 \sin i = 8.5\ R_\odot$, so $R_1 \sin i / a_1 \sin i = 0.82$, indicating that the K1 III star fills a substantial fraction of its Roche lobe. Since there is no photometric evidence of eclipses, $R_1 + R_2 < a \cos i$, where R_1 and R_2 are the radii of the primary and secondary, respectively, and a is the semimajor axis of the relative orbit. From the mass ratios in Table VI, the maximum value of $a \sin i = 30\ R_\odot$ and the upper limit to the inclination therefore is 75°. As the mass ratio M_1/M_2 decreases, the maximum inclination also decreases. Thus, the inclination of the system is $58° \pm 17°$ and the secondary is probably a G or K dwarf.

Although Burke *et al.* (1982) considered a two-spot model to explain their double-peaked light curve, we note that the large relative radius of the K1 III star suggests that sizeable

TABLE VI. Mass and inclination limits.

M_1 ($M_\odot$)	$M_2(i=90°)$ ($M_\odot$)	M_1/M_2	$M_2(u)$ ($M_\odot$)	i (°)
1.8	0.74	2.43	1.2	44
1.6	0.70	2.29	1.2	42
1.4	0.65	2.15	1.2	40
1.2	0.59	2.03	1.1	40

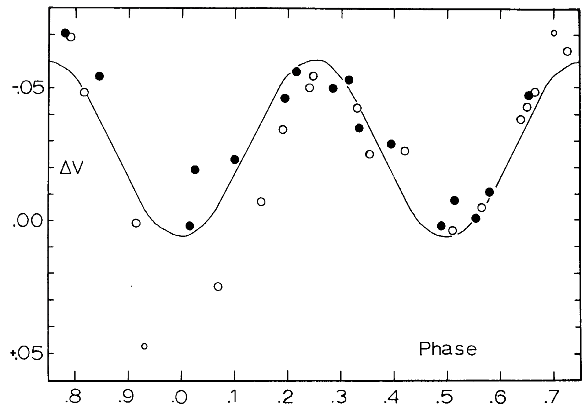

FIG. 5. Double-peaked light curve of HD 136905 = GX Librae based on nightly means from 1982 and 1984. Dark circles are from Burke *et al.* (1982); light circles are from Table III of this paper, the two smaller ones of relatively low statistical weight. Phase is computed with the orbital ephemeris in equation (1), where zero phase is conjunction with the K1 III star in front. The solid curve is a Fourier fit and, as explained in the text, represents ellipsoidal variability of the tidally elongated K1 III star.

ellipsoidal light variations should be present and therefore considered as an alternative explanation. Such ellipsoidal light variations, although not extremely common in chromospherically active stars, have been found in some. Two of the more well-known cases are ζ And (Gratton 1950) and HR 8575 = V350 Lac (Herbst 1973). For comparison, $R_1 \sin i / a_1 \sin i = 0.75$ for HR 8575 and 0.82 for HD 136905, indicating that both stars fill a similar fraction of their Roche lobes.

The 1982 photometry of Burke *et al.* (1982) and the 1984 photometry from Table III are plotted together in Fig. 5, where each point is a nightly mean and phase is computed with the ephemeris

$$2{,}445{,}073.005 + 11^{d}1345\ n \tag{1}$$

taken from the orbital elements in Table IV. The initial epoch here is T_0 advanced $\frac{1}{4}P$, i.e., conjunction with the K1 III star in front. We see that the 1984 data define essentially the same double-peaked light curve found in 1982.

To test the hypothesis of ellipsoidal variability, we determined the period from the photometry alone. We fit the light curve by least squares using a Fourier series containing only terms in 2θ. The smallest variance was found with a period of $11^{d}1345 \pm 0^{d}0030$. The time of conjunction corresponding to that best fit was JD $2{,}445{,}072.988 \pm 0^{d}003$. Thus, the photometry and the spectroscopy yield periods which are identical, with an uncertainty of only $\pm 0^{d}003 = 0.03\%$. Moreover, the photometry and the spectroscopy yield times of conjunction differing by only $0^{d}017$, which is less than the combined uncertainty. This excellent consistency in both aspects persuades us to conclude that the principal variability results from the ellipticity effect. The solid curve in Fig. 5 represents the Fourier fit and shows that the full amplitude is $0^{m}067 \pm 0^{m}002$ in V.

There is some suggestion that the light curve has changed between 1982 and 1984, in the vicinity of the minimum around $0^{P}0$. This, along with the somewhat unequal heights of the two maxima, could be a consequence of starspot activity, but the photometry available does not warrant more discussion at this time.

Finally, with the advent of sophisticated light-curve modeling programs, a simultaneous solution of all effects could be made once additional photometry has been obtained. In principle, the light-curve solution of the ellipsoidal variation could result in the determination of the mass ratio. In practice, there are so many assumptions that must be made that the properties of an unseen secondary are usually poorly constrained (e.g., Gulliver *et al.* 1985).

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